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Digital Enhancement of Flow Field Images

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single image from the photograph in figure 1 is used to illustrate the enhancement processing.

Digitizing the Photograph

The Eikonix digitizing camera consists of a linear array of 2048 photodiodes that is moved automatically in 2048 discrete steps in a direction orthogonal to the array. This process converts the visual information into a digital image, i.e., a 2048 by 2048 digital picture element (pixel) array. Each digitized pixel location is assigned an integer gray level value from 0 (black) to 255 (white), determined by the brightness of the image at that location. This digital array is then transmitted to the image processing system where it can be displayed and processed as a digital image. The Eikonix camera was used to digitize the photograph in an area of interest, in this case the outlined area in figure 1 where the vortex is about to strike the airfoil.

Although the Eikonix camera can generate digital images as large as 2048 by 2048, only a 512 by 512 digital image was produced. The reason for this is that other components of the image processing system are optimized to process 512 by 512 images, and this spatial resolution was considered sufficient to resolve the structural information desired. It takes the Eikonix camera approximately 1 minute to scan the area of interest and generate a corresponding 512 by 512 digital image. Figure 3 shows the digitized image taken from the outlined area in figure 1. This 512 by 512 image will be used to illustrate the effect of various enhancement techniques.

Enhancement Sequence

Once a digital image has been generated (fig. 3), the image processing system can be used to interactively analyze the image to provide quantitative image information that can be used to efficiently implement the subsequent enhancements. An image histogram is an effective method of extracting some of this quantitative information by displaying the gray level frequency distribution.

Figure 4 illustrates the histogram of the image in figure 3. This histogram, which is generated in less than 5 seconds by the IP8500 system, facilitates subsequent image enhancement. Histograms are generated pixel by pixel, by accumulating each pixel value into a 256-element integer array. In other words, for each gray level, the number of pixels in the image with that value is counted. The histogram array is then normalized and plotted (in red) as a percentage of total pixels. Also plotted (in black) on the histogram is the cumulative histogram curve, which indicates the number of pixels with a gray level value less than or equal to the specified value. The histogram display in figure 4 also includes the image for reference and some image statistics, which will be useful in the enhancement process.

The low contrast of the image in figure 3 is graphically illustrated in the histogram; the image standard deviation is small (approximately 17), and most of the pixels in the image have a gray level value within a narrow range between 127 and 180. In this particular image, the large concentration of pixels with a value between 170 and 180 represents (primarily) the pixels that form the light gray background in the image. The pixels in the area of interest in this image, the higher density (darker) vortex structure, have gray level values ranging from 127 to 170.

Improving the contrast. The first major enhancement of the image in figure 3 was to improve the overall contrast of the image and isolate the vortex from the surrounding background noise. This was accomplished with linear contrast stretching, an image processing technique that improves the contrast of the image by "clipping" gray level values outside a specified range, while "stretching," yet preserving, the natural ordering of gray levels within this specified range. The ordering of the data must be preserved so that the image data maintain their correlation with physical density. (Because fig. 3 is a negative image, the brightness of the image is inversely proportional to the density of the smoke.) The quantitative image information obtained from the histogram of the low contrast image (fig. 4) was used to determine the gray levels at which clipping will occur.

Figures 5 and 6 show the enhanced image and its histogram after linear contrast stretching. Note that a small range of gray level values in the original low contrast image have been mapped onto a much larger gray level range in the enhanced image; thus, contrast is improved (the standard deviation has been increased to 38) while the natural ordering of the data is preserved. Specifically, pixels with gray level values between 127 and 170 have been assigned new gray level values that are linearly interpolated from 0 to 255. All the pixels in the original image with gray level values between 170 and 255 (corresponding to the light background) have been assigned a value of 255 and are displayed as white in the enhanced image. Similarly, those few pixels in the original image with gray level values less than 127 have been assigned a value of 0 and are displayed as black. (Scaling considerations dictate that the percentage of pixels with values of 0 or 255 should not be plotted on the histogram in fig. 6, since clipping causes the number of pixels with these values to be so great.)

Contrast stretching is implemented interactively on the image processing system. The user selects the two end points of a gray level range in the original low contrast image that will be stretched (i.e., interpolated) onto the entire gray level range in the enhanced image. A trackball can be used to interactively select the end points, and the effect of the selection on the image is displayed immediately. This interaction allows the user to continuously adjust the end points until a desired enhanced image is displayed. The details of the method by which this technique is implemented interactively on the image processing system are described in the appendix.

Linear contrast stretching fulfilled the objective of improving image contrast and isolating the area of interest while preserving the "integrity" (i.e., gray level ordering) of the data. In an attempt to further improve the contrast of the image, a second technique was used—histogram equalization. This is a standard image-processing technique (ref. 3) that requires no interactive user input and is designed to increase the contrast of an image by modifying the shape of its histogram. Histogram equalization is accomplished by "consolidating" gray levels, i.e., assigning the same gray level in the enhanced image to pixels with gray level values that differ by a small amount in the original image in an attempt to produce a more uniform gray level distribution.

The contrast-stretched image in figure 5 was used as input, and the resulting image after histogram equalization is shown in figure 7. The near uniformity of the associated histogram in figure 8 is evident; i.e., the cumulative histogram curve approximates a straight line. (It is impossible to produce a perfectly uniform histogram given the discrete nature of the gray levels.) Histogram equalization has further increased the contrast of the image (standard deviation of 65). However, in this case, the use of histogram equalization is problematic because the technique alters the image data by gray level consolidation and thereby effectively reduces gray level resolution. Because the gray level resolution of the stretched image was already low, histogram equalization was rejected as a second enhancement step, and the contrast-stretched image in figure 5 was used as an input for all subsequent enhancements.

Contouring the image. The next enhancement step was to highlight the contrast variations within the vortices (since they are correlated with the physical density variations defining the structure of the vortex). This was accomplished with an interactive routine that produces contours based on a technique known as gray level slicing. This technique maps selected gray levels to black, thereby outlining contours of constant gray level (i.e., density) as illustrated in figure 9. The user of this technique visually and/or numerically chooses gray levels that are immediately displayed as black in the image. The effect on the image histogram of mapping the selected gray levels to black is shown in figure 10. Gray level slicing produces a contouring effect that outlines subtle gray level variations and serves to highlight key structural features. The method by which this technique was implemented interactively with the image processing system is described in the appendix.

Although the image in figure 9 highlights the structure of the vortex, the gray level contours are badly fragmented because of the quantization noise induced (by analog-to-digital conversion) during the digitization process. Quantization noise is prominent in this case because of the very low contrast of the original photograph. To suppress quantization noise, the image in figure 5 was processed with various spatial filters prior to gray level slicing. The objective of the filtering was to make the gray level contours more continuous. By experimentation it was determined that the most effective filter was a spatially localized low-pass filter, in particular a 3 by 3 moving-average filter applied several times (ref. 3). The resulting filter was large enough to remove the localized quantization noise present in the images, yet small enough that no significant large-scale spatial information was altered. The number of times the filter was applied was dependent on the amount of quantization noise present in the image and was experimentally determined by analyzing the effect of the filtering after each iteration. Too few iterations will not significantly improve the continuity of the gray level contours, and too many iterations will significantly blur the image. Figure 11 shows the effect of filtering the image in figure 5 three times before applying the gray level slicing technique. To use the fullest possible (integer) arithmetic precision available on the image processor, it is desirable to stretch the image before filtering rather than stretch the filtered image. The effect of the filtering becomes more evident after the image is again enhanced with the gray level slicing technique, as shown in figure 12. The gray level contours are continuous and sharp, clearly defining the structural features, i.e., the density variations of the reflective particles within the vortex.

The previously discussed enhancements provide an improved image for physical interpretation and meet the final enhancement goal of generating publication-quality figures that convey significant information to other researchers. However, as a further enhancement step, a capability to display the image with a variety of backgrounds was also developed. In figure 13, all image data except the contour lines were mapped to white to produce a traditional black on white contour plot of the vortex structure. As an alternative, the image can also be displayed with a pseudocolor technique that serves to further enhance the contrast variations within the image, as seen in figure 14. This technique is implemented by mapping the gray level range to a standard color spectrum as described in the appendix. This pseudocolor display is effective for interpretation because the human eye can distinguish variations in color much more easily than variations in gray levels.

Printing the Enhanced Images

As each enhancement is completed, the resulting digital image can be sent by means of an Ethernet connection to the Dicomed film recorder. The image can be recorded on film by using color or black and white negatives or Polaroids. This is accomplished by scanning the displayed image line by line and, for each pixel, transmitting to the recorder an exposure value determined by the gray level value of the pixel. The beam of light emitted by a cathode-ray tube in the recorder is projected through a lens and focused on the film plane for an amount of time determined by the exposure values. The recording process takes approximately 1 minute to convert a 512- by 512-pixel image into a 4- by 5-in. black and white Polaroid.

Additional Applications

The flexibility of the image processing system allows enhancements to be applied to a variety of applications. Since different applications have their data in different formats and media, this section describes several methods for image data input and output.

Figures 15 and 16 show the effect of the enhancement process on a wind-tunnel photograph generated by using a water vapor screen technique to depict flow density (ref. 4). Vapor screen photographs of vortices are also typically characterized by low contrast and high background noise. In this image, flow is out of the picture along the trailing edge of a wing. The same enhancement sequence previously described was used to produce the enhanced image in figure 16.

Enhancement techniques can also be applied to computational fluid flow images generated on the VPS-32 supercomputer at Langley and input to the image processing system by means of the Ethernet connection. The computer-generated image in figure 17 uses color to display the Mach number of flow through a nozzle. Although the overall contrast of this original was good, the contrast variations were not clearly defined until the image was digitally enhanced, producing contour lines of constant Mach number as shown in figure 18.

All the enhancements shown involved a static analysis of a single image. However, the speed of the image processing system and of the Gould real-time disk (see fig. 2) makes it possible to apply these enhancements dynamically to a sequence of images recorded on videotape. A sequence of wind-tunnel images recorded on videotape can then be digitized into 512 by 512 digital images and stored on the real-time disk. The real-time disk is capable of reading and writing a sequence of digital images at video rates so that the enhancements may be interactively applied to a series of images (ref. 5). The resulting enhanced images can then be recorded on videotape or used to produce a sequence of photographs.

Concluding Remarks

It has been demonstrated that image enhancement can be effectively applied to flow field images. This process provides researchers with new images that can be more easily and accurately interpreted. In particular, the structure and location of flow field features can be clearly determined without relying on the visual analysis and drawing abilities of the researcher. Digital flow field processing represents a new interactive analysis capability at Langley Research Center, and the enhanced images produced can be created in a matter of minutes, rather than days. In addition, these new images provide a more effective means of conveying the results to others through publications, slide presentations, and videotapes.

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Hampton, Virginia 23665-5225
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Appendix

Implementation Details

The purpose of this appendix is to provide additional information about some of the image processing techniques discussed in the body of this paper.

Look-Up Tables

A look-up table (LUT) provides much of the speed necessary for the interactive use of image processing techniques such as contrast stretching, gray level slicing, and pseudocoloring. A LUT provides a means of interactively modifying the displayed image pixel values without changing the original image pixel values stored in memory. A LUT is a one-dimensional hardware array logically located between image memory and the display device, as shown in figure 19. The array is indexed from 0 to 255, corresponding to the possible gray level values of a pixel. The gray level value of a pixel stored in memory is used to index the array, and the value of each element in the array (from 0 to 255) determines the gray level that will be displayed for that pixel. As an example, every pixel in the image with a gray level value of 99 in the original image will be displayed with a value of 55. This allows the image to be interactively modified, since only the 256 LUT elements must be modified rather than the $(512)^2 = 262,144$ pixel values stored in memory.

Linear Contrast Stretching

Figure 19 shows the use of a LUT for implementing the linear contrast-stretching technique. As discussed previously, the technique involves choosing 2 gray level values (here 79 and 171) in the original image and linearly mapping each gray level value within this specified range onto the entire gray level range from 0 to 255. All gray level values that fall below or above the specified range are clipped to 0 (black) or 255 (white), respectively. The user can interactively specify (i.e., with a trackball) the 2 gray levels, and the 256 LUT elements are then immediately updated, and the modified image is displayed. This process can be repeated until the desired enhancement is achieved and then, if desired, the original image pixel values can be passed through the LUT to generate the modified values stored in memory.

Gray Level Slicing

Gray level slicing to contour images is also accomplished with a LUT. A trackball can be used to interactively select gray levels to be "blackened." The selected gray level values are mapped to 0 in the LUT, and the corresponding pixels are immediately displayed as black. The interactive nature of the process allows the user to visually select and change several consecutive gray levels to produce a continuous contour.

Pseudocoloring

Look-up tables also provide a means for transforming a gray level image into a color image. This process is known as pseudocoloring and is based on the use of three LUT's corresponding to the desired red, green, and blue components of the enhanced image. Thus, pixel values in the original image will be mapped into three LUT's, and three values, each ranging from 0 to 255, will be used to modulate the red, green, and blue cathode-ray tube beams in the display device. This technique is particularly effective for making contrast variations within an image more evident. For the images in this paper, the red, green, and blue look-up tables were designed to model an intuitive "rainbow" spectrum.

References

1. Booth, E. R., Jr.; and Yu, J. C.: Two-Dimensional Blade-Vortex Flow Visualization. *AIAA J.*, vol. 24, no. 9, Sept. 1986, pp. 1468-1473.
2. George, A. R.: Helicopter Noise: State-of-the-Art. *J. Aircr.*, vol. 15, no. 11, Nov. 1978, pp. 707-715.
3. Rosenfeld, Azriel; and Kak, Avinash C.: *Digital Picture Processing*, Second ed., Volume 1. Academic Press, Inc., 1982.
4. Miller, David S.; and Wood, Richard M.: *Lee-Side Flow Over Delta Wings at Supersonic Speeds.* NASA TP-2430, 1985.
5. Kaczynski, Mary-Anne: Dynamic Data Visualization Using the IP8500 and RTDD. Paper presented to the Gould Users' Group Conference (Boston, Massachusetts), Nov. 4-6, 1986.

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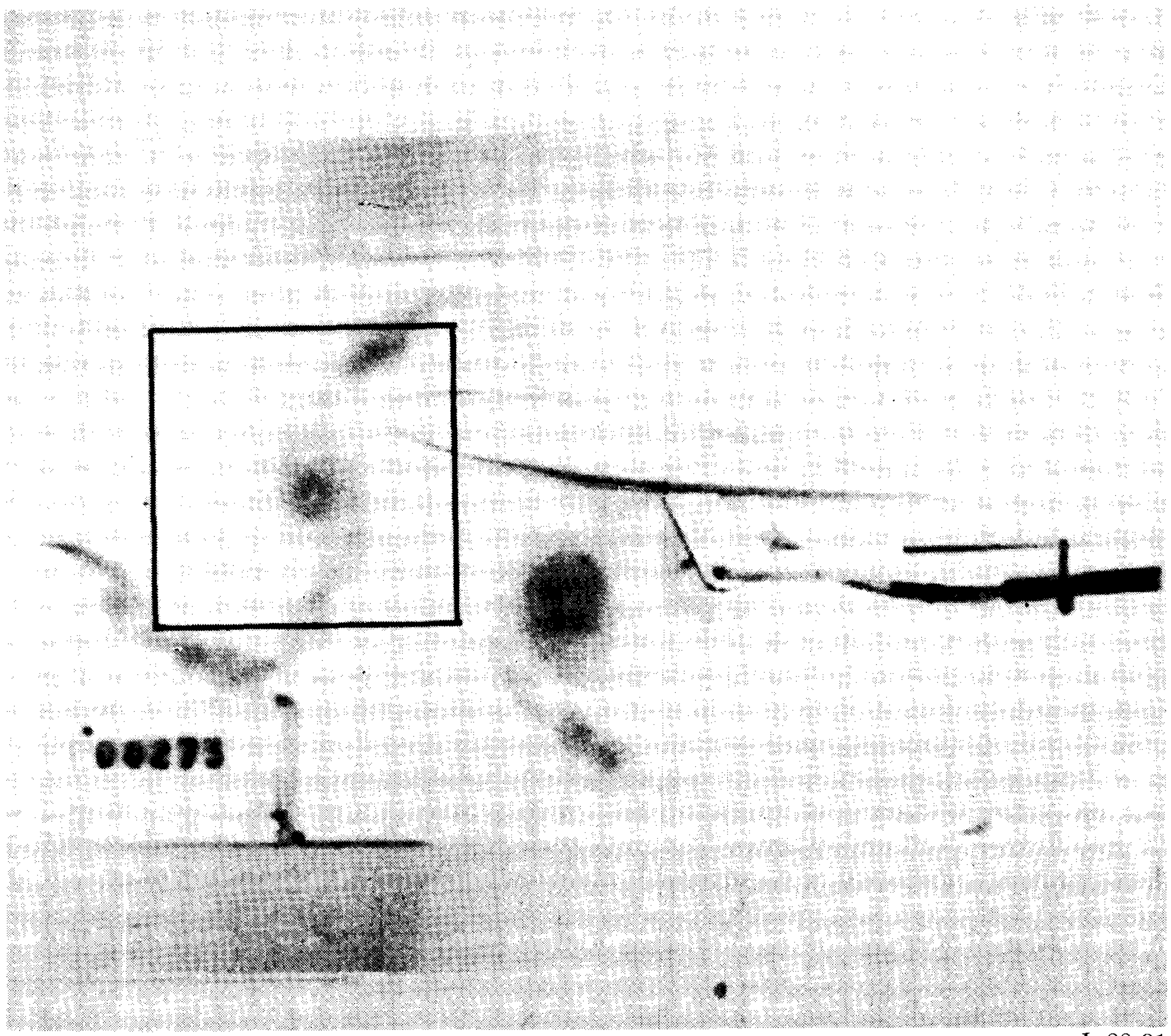

Figure 1. Negative of original wind-tunnel photograph.

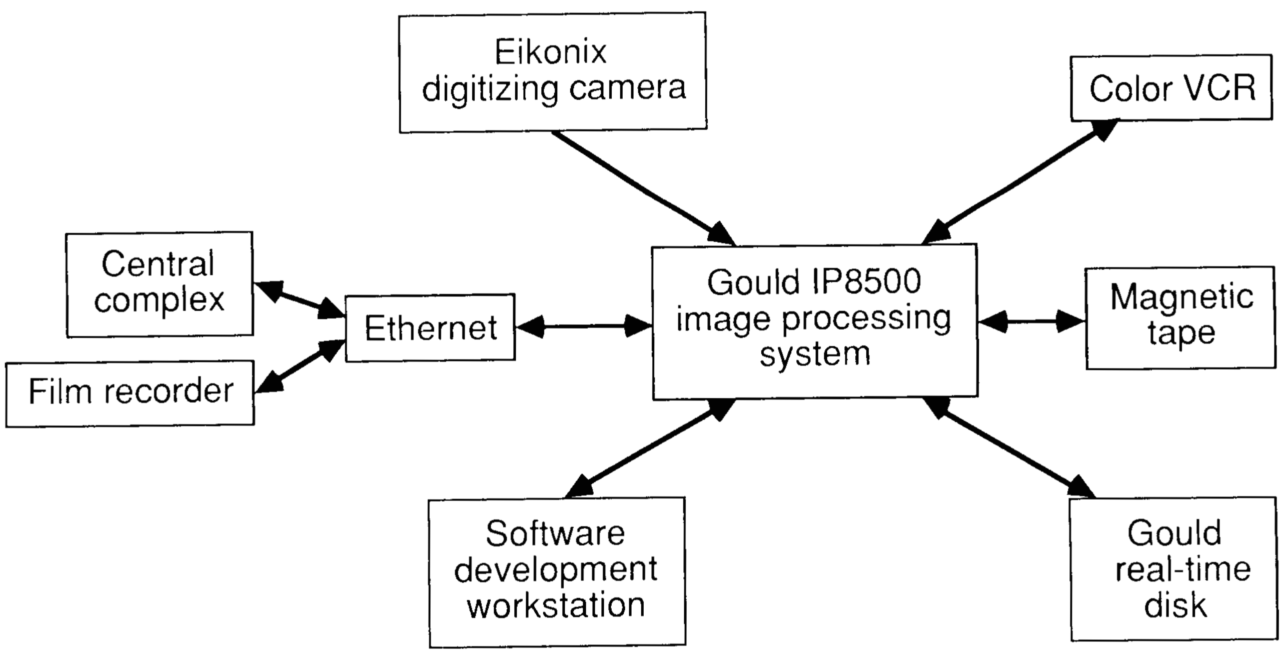

Figure 2. Current configuration of the image processing laboratory at Langley.

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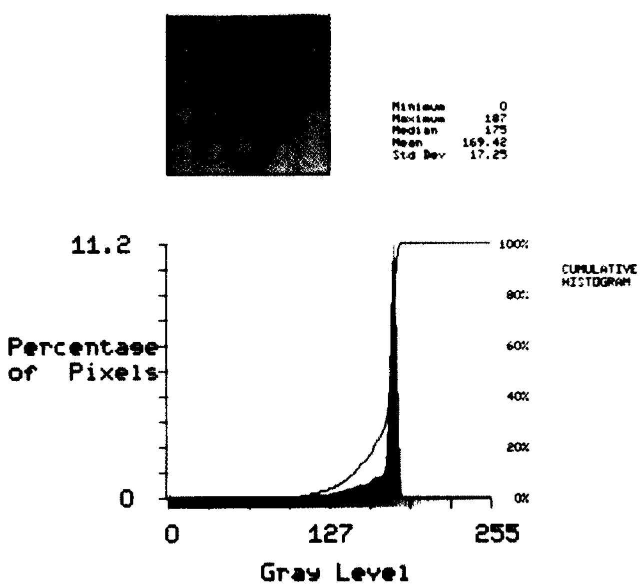

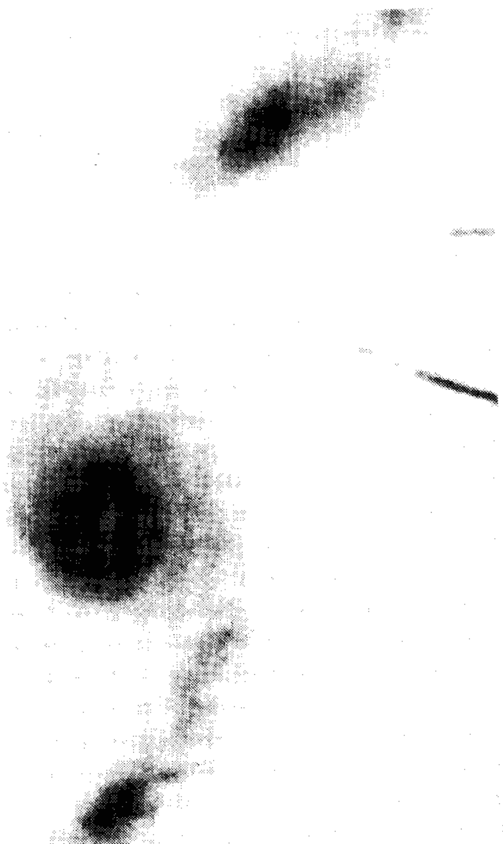

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Figure 5. Contrast stretching applied to image.

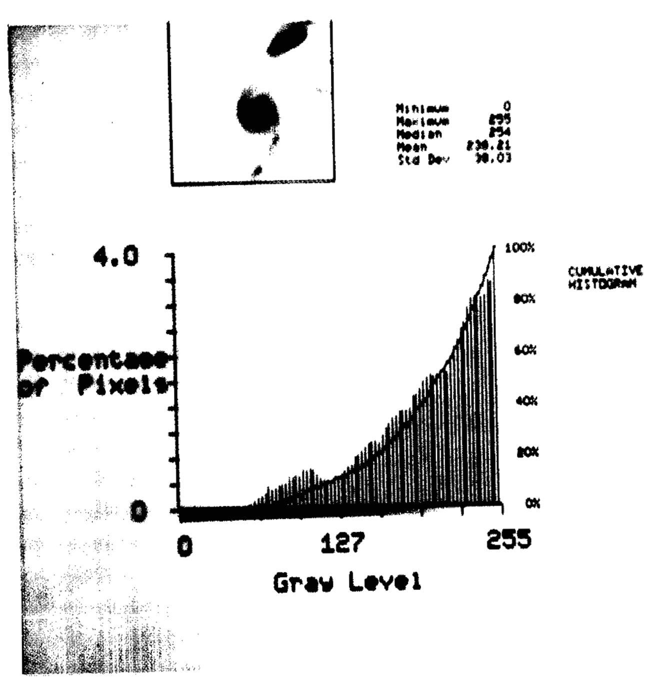

Figure 6. Histogram display of contrast-stretched image.

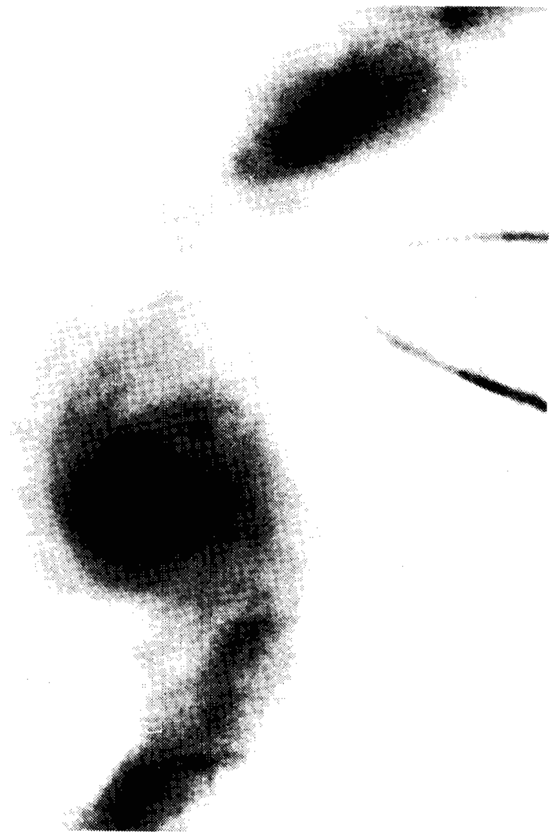

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Figure 7. Histogram equalization applied to contrast-stretched image.

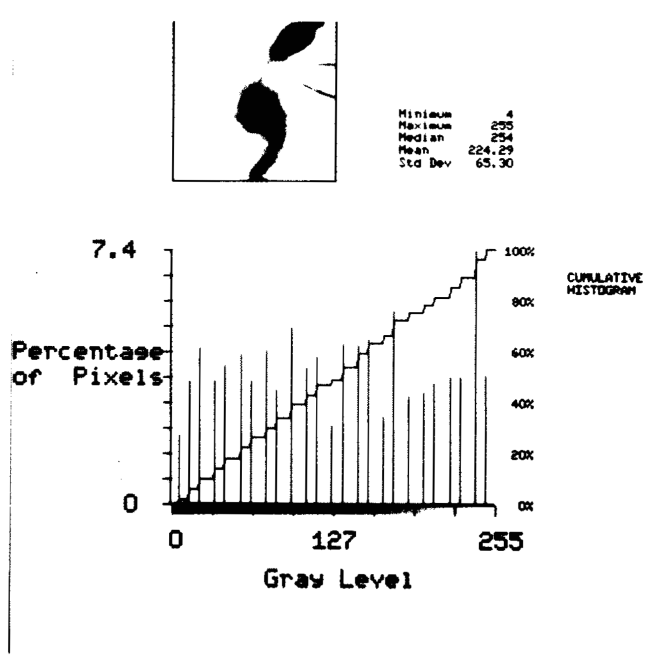

Figure 8. Histogram display of equalized image.

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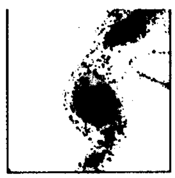

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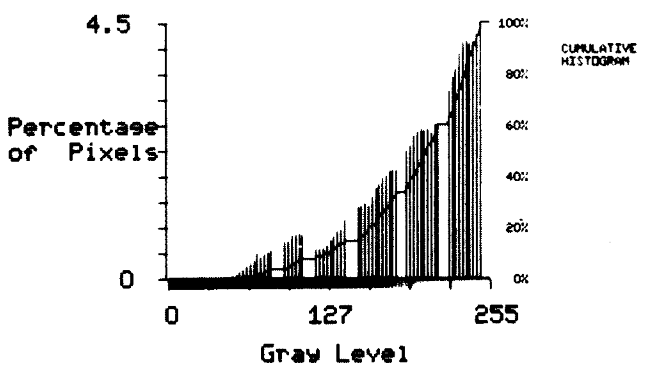
Maximum	255
Median	254
Mean	226.76
Std Dev	65.81



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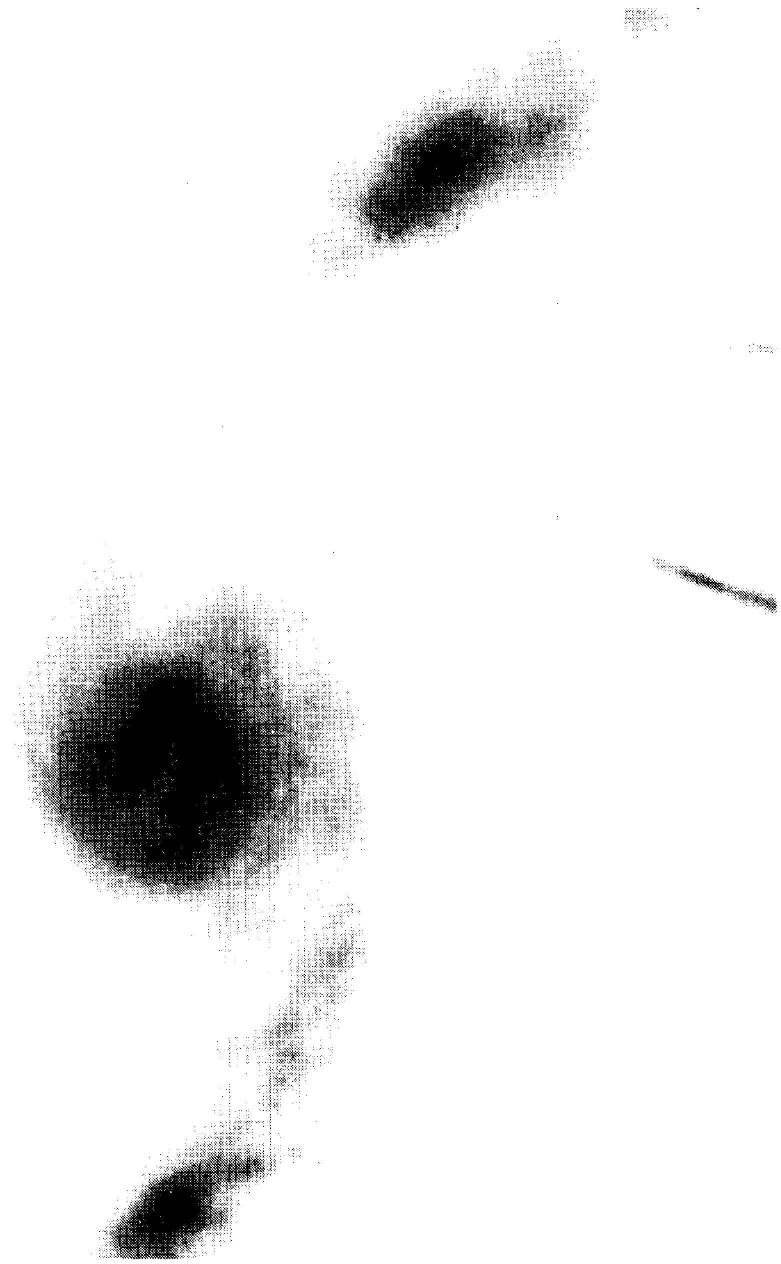

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Figure 11. Filtering applied to contrast-stretched image.

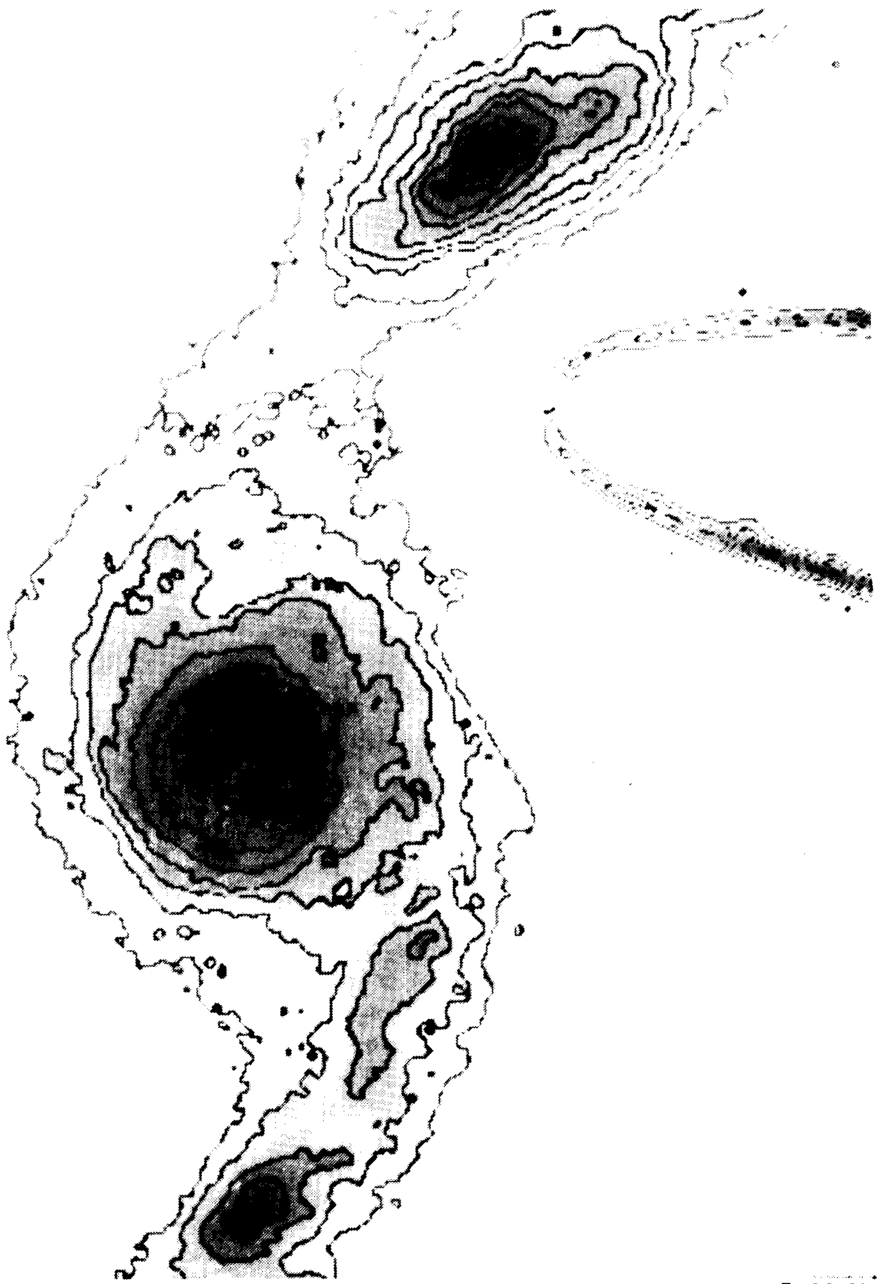

Figure 12. Contouring applied to filtered image.

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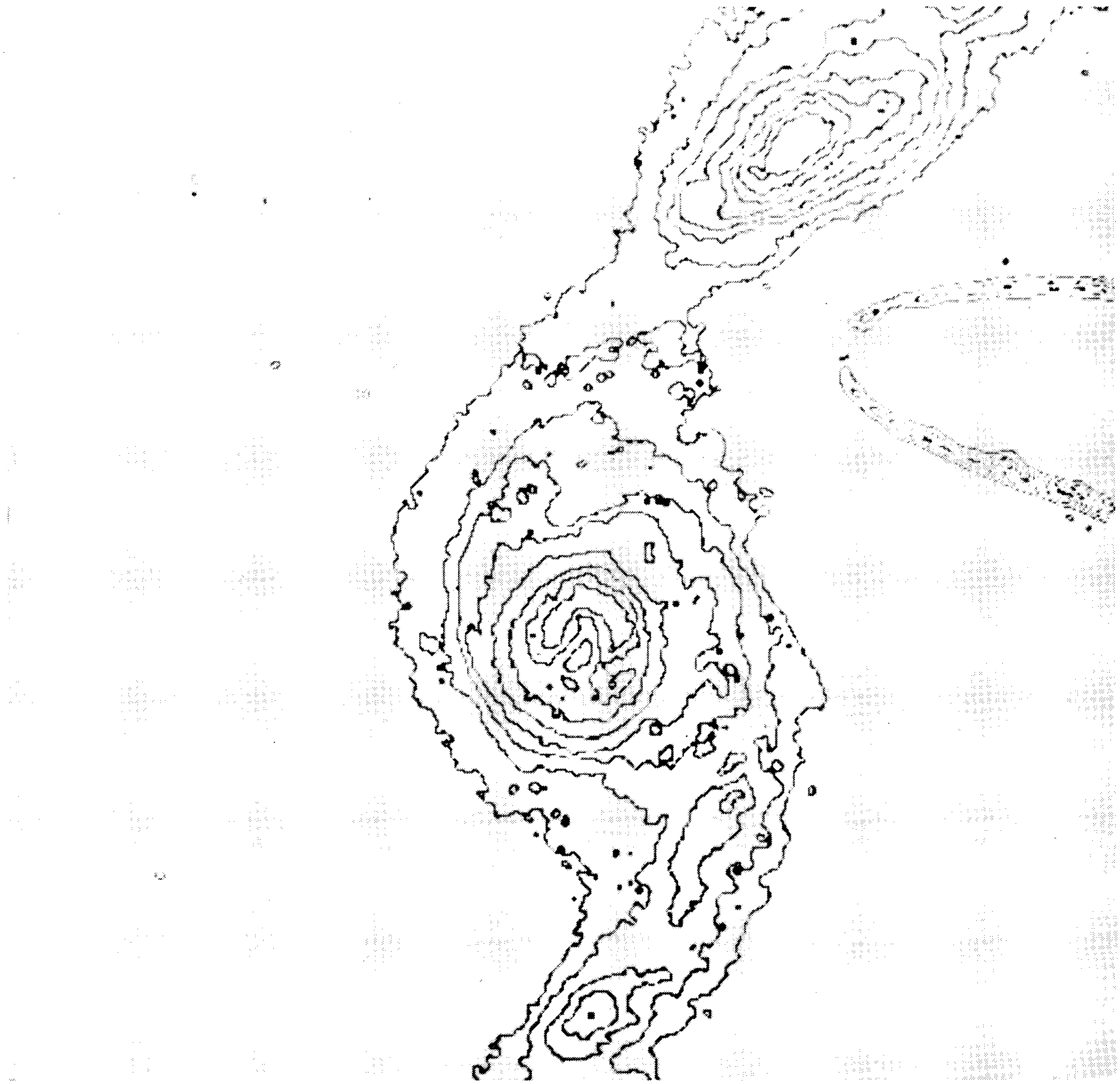

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Figure 13. Contoured image with white background.

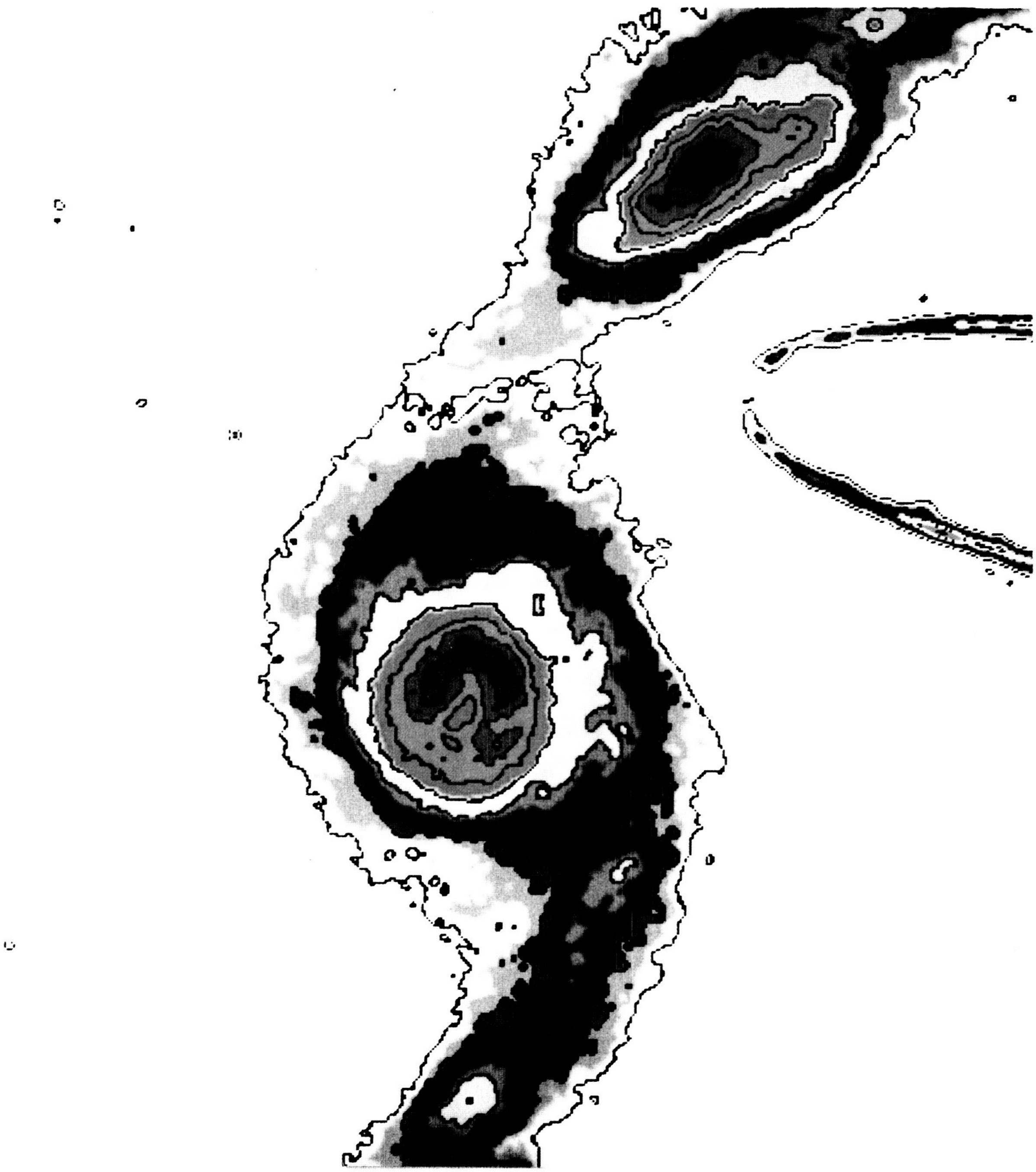

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Figure 14. Contoured image with pseudocolored background.

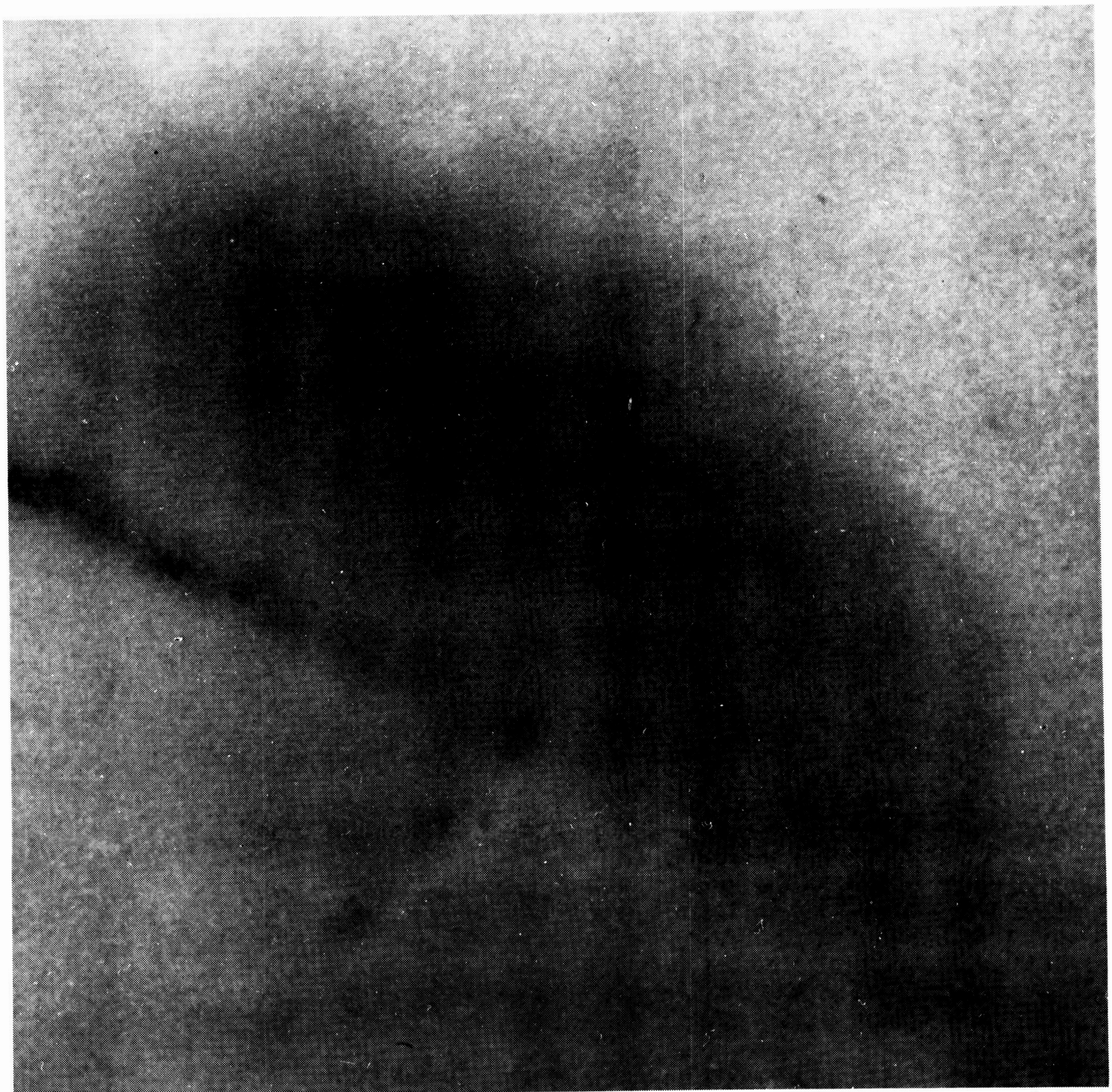

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Figure 15. Original water vapor screen image.

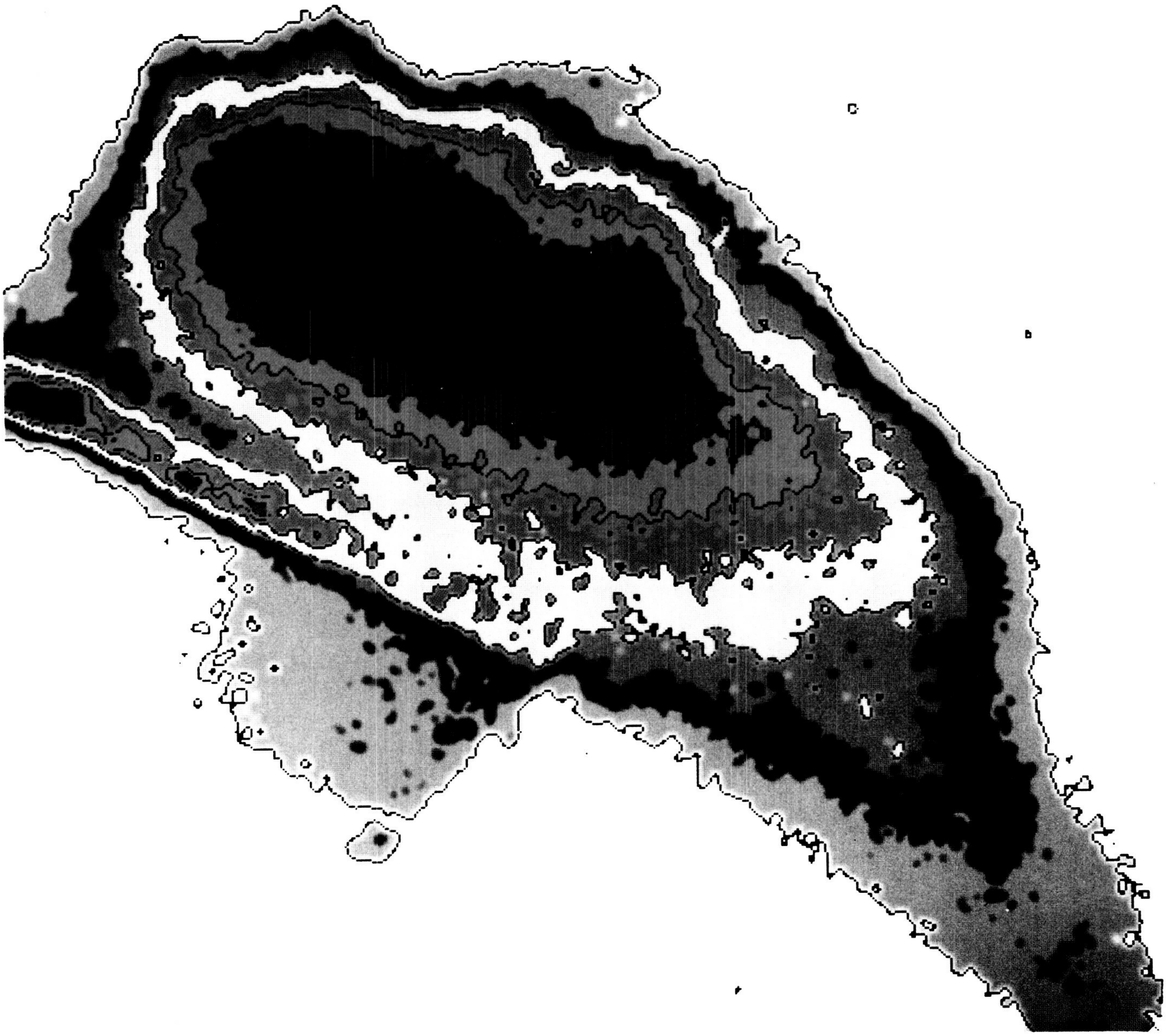

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Figure 16. Enhancements applied to water vapor screen image.

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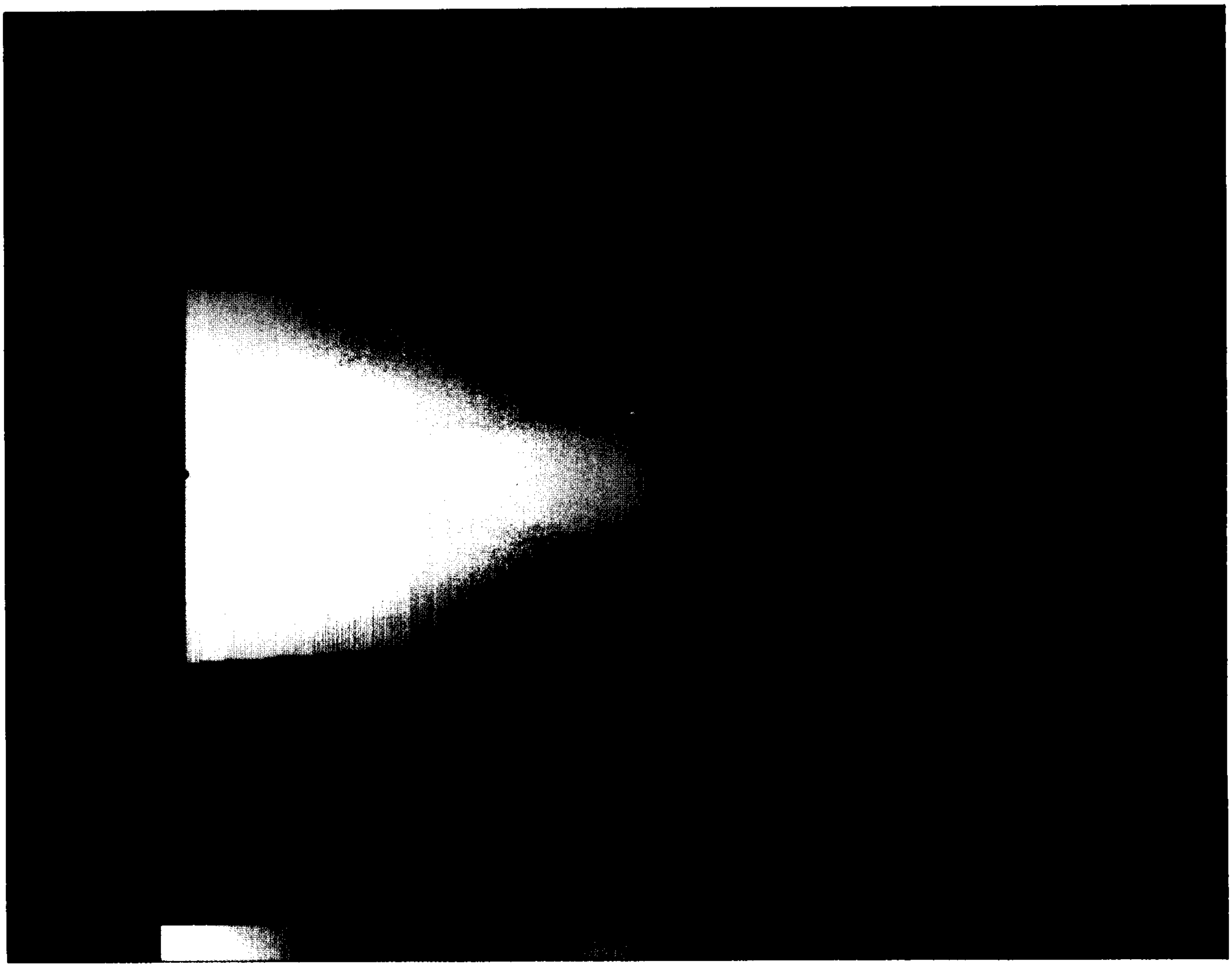

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Figure 17. Original computer-generated fluid flow image.

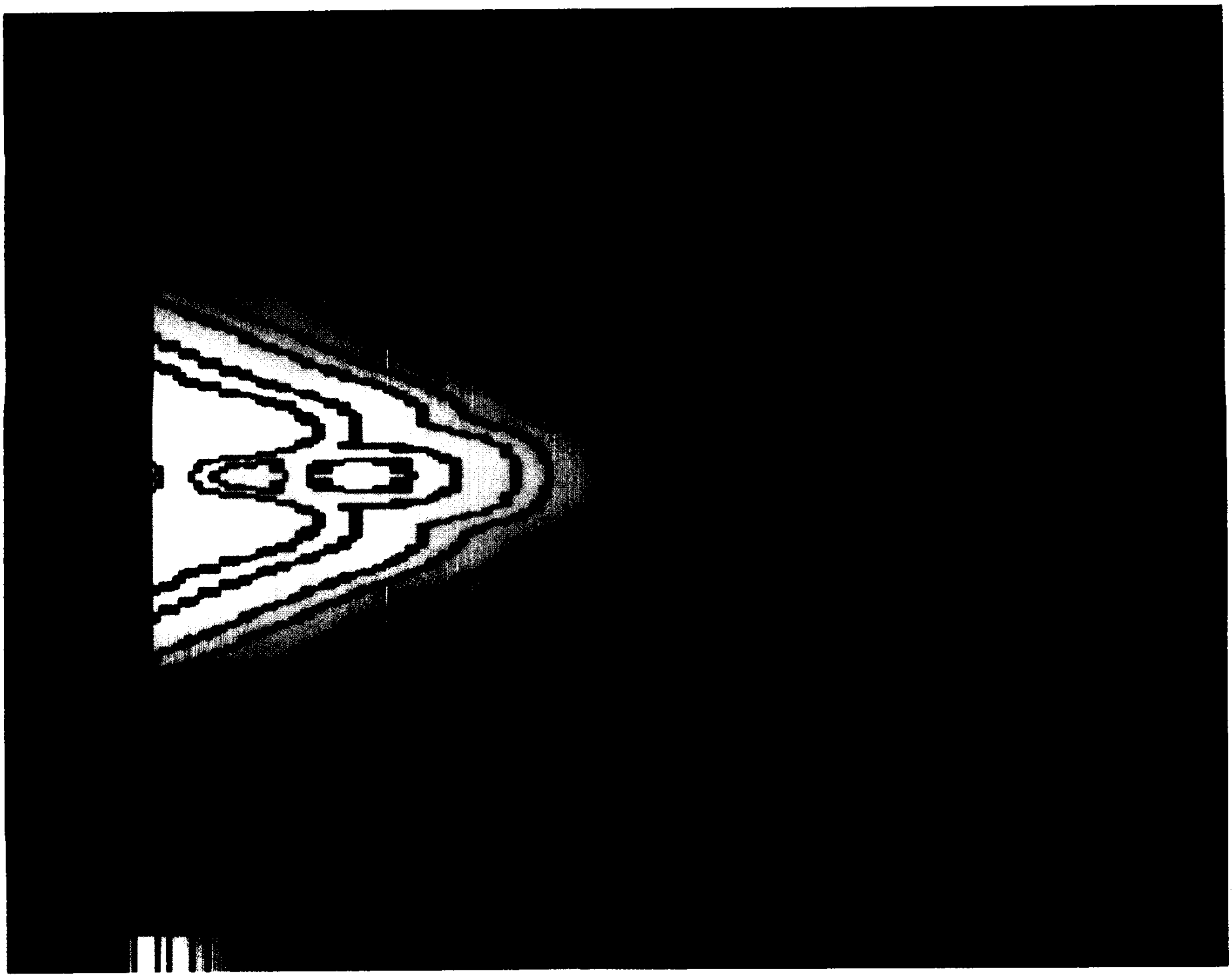

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Figure 18. Contouring applied to computer-generated image.

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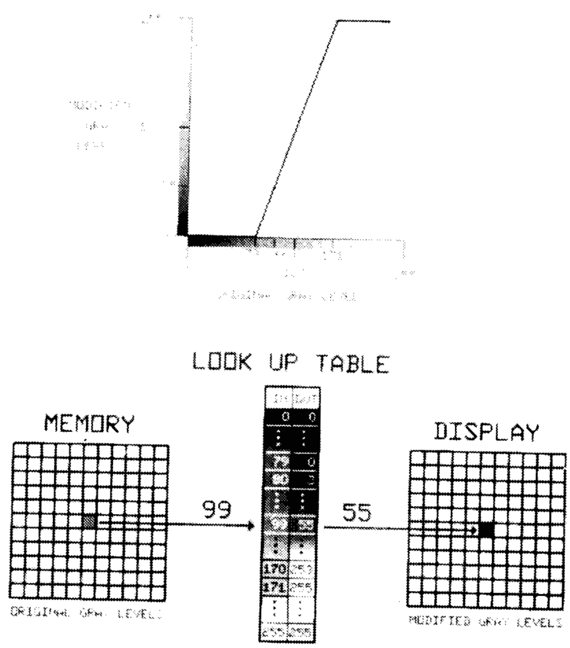

Figure 19. Computer implementation of linear contrast stretching.

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15. Supplementary Notes

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16. Abstract

Most photographs of experimentally generated fluid flow fields have inherently poor photographic quality, specifically, low contrast. Thus, there is a need to establish a process for quickly and accurately enhancing these photographs to provide improved versions for physical interpretation, analysis, and publication. This report describes an interactive sequence of digital image processing techniques that have been demonstrated to effectively enhance such photographs.

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